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One-Particle Inclusive $B_s \rightarrow \bar{D}_s X$ Decays

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Abstract

We discuss one-particle inclusive $B_s \rightarrow \bar{D}_s X$ decays using a QCD based method already applied to $B \rightarrow \bar{D} X$. A link between the right charm non-perturbative form factors of the semi-leptonic decays and those of the non-leptonic decays is established. Our results are compatible with current experimental knowledge.

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1 Introduction

Some time ago, a QCD based method was proposed to describe $B \rightarrow \bar{D}\ell\nu X$ decays, which relies on a short distance expansion (SDE) and on the heavy quark effective theory (HQET) [1]. The non-perturbative form factors of the singlet operators were parameterized using the Isgur-Wise function. More recently this method was extended to one-particle inclusive non-leptonic B decays [2]. In this case, we have to perform a $1/N_C$ expansion, which allows to factorize the matrix elements. One of the goal of this work is to clarify the link between the matrix elements which were encountered in the semi-leptonic one-particle inclusive B decays [1] and those of the non-leptonic one-particle inclusive B decays encountered in [2]. In fact we shall prove that these matrix elements are universal. We shall then apply this method to one-particle inclusive $B_s \rightarrow \bar{D}_s X$ and $B_s \rightarrow D_s X$ decays.

It is shown in [2] that the one-particle inclusive decays of a B meson into a vector D meson seem to be, in this framework, well understood whereas decays of a B meson into a pseudo-scalar D are troublesome, i.e. the decay widths and spectra for $B \rightarrow \bar{D}^*/D^* X$ admixtures look to be described correctly, on the other hand the predictions for $B \rightarrow \bar{D}/DX$ admixtures decay widths and spectra do not reproduce the experimental data. Most troublesome is the fact that the spectra are not even described correctly for large transferred momentum. According to our method we expect to describe the experimental data for large transferred momentum particularly well.

Keeping in mind that some problems arose in the description of $B \rightarrow \bar{D}/DX$ decays, we apply the method developed for these decays to $B_s \rightarrow \bar{D}_s X$ and $B_s \rightarrow D_s X$ decays. The effective Hamiltonian is identical in both cases. One-particle inclusive $B_s \rightarrow \bar{D}_s X$ decay widths have been measured by ALEPH. There are measurements for semi-leptonic [5] as well as for non-leptonic [7] decays.

The decay rates we are computing can be used to study one-particle inclusive CP asymmetries in the B_s system [6], which would allow an extraction of the weak angle γ which is known to be difficult. This study of $B_s \rightarrow D_s X$ decays could also allow to get a better understanding of the problems encountered in $B \rightarrow DX$ decays [2]. They are also interesting for experimental physics especially in the perspective of B factories as the presently available data on one-particle inclusive $B_s \rightarrow D_s X$ decays is sparse.

In the following section, we shall establish the link between the form factors of the semi-leptonic decays and those of the non-leptonic decays for the right charm $\bar{b} \rightarrow \bar{c}$ transition.

2 From semi-leptonic to non-leptonic decays

We shall consider right charm decays $B \rightarrow \bar{D}X$, i.e. $\bar{b} \rightarrow \bar{c}$ transitions. The central quantity in the semi-leptonic case as well as the non-leptonic case is the function G given by

$$G(M^2) = \sum_X \left| \langle B(p_B) | H_{eff} | \bar{D}(p_{\bar{D}}) X \rangle \right|^2 (2\pi)^4 \delta^4(p_B - p_{\bar{D}} - p_X), \quad (1)$$

where $|X\rangle$ are momentum eigenstates with momentum p_X , H_{eff} is the relevant part of the weak Hamiltonian and $M^2 = (p_B - p_{\bar{D}})^2$ is the invariant mass. The states $|X\rangle$ form a complete set, especially $|X\rangle$ can be the vacuum in the semi-leptonic case, e.g. $B \rightarrow \bar{D}\ell\nu$ contributes to $B \rightarrow \bar{D}\ell\nu X$. This function G is related to the decay rate under consideration by

$$d\Gamma(B \rightarrow \bar{D}X) = \frac{1}{2m_B} d\Phi_{\bar{D}} G(M^2), \quad (2)$$

where $d\Phi_{\bar{D}}$ is the phase space element of the final state \bar{D} meson. The relevant weak Hamiltonian is given by

$$H_{eff} = H_{eff}^{(sl)} + H_{eff}^{(nl)}, \quad (3)$$

where the semi-leptonic and non-leptonic pieces are given by

$$H_{eff}^{(sl)} = \frac{G_F}{\sqrt{2}} V_{cb} (\bar{b}c)_{V-A} (\bar{\ell}\nu)_{V-A} + h.c., \quad (4)$$

$$\begin{aligned} H_{eff}^{(nl)} = & \frac{G_F}{\sqrt{2}} V_{cb} V_{ud}^* \left((\bar{b}c)_{V-A} (\bar{u}d)_{V-A} + (\bar{b}T^a c)_{V-A} (\bar{u}T^a d)_{V-A} \right) + \\ & \frac{G_F}{\sqrt{2}} V_{cb} V_{cs}^* \left((\bar{b}c)_{V-A} (\bar{c}s)_{V-A} + (\bar{b}T^a c)_{V-A} (\bar{c}T^a s)_{V-A} \right) + h.c., \end{aligned} \quad (5)$$

where we have neglected the penguins and the Cabibbo suppressed operators. The function G can be written as

$$G(M^2) = \sum_X \int d^4x \langle B(p_B) | H_{eff}(x) | \bar{D}(p_{\bar{D}}) X \rangle \langle \bar{D}(p_{\bar{D}}) X | H_{eff}(0) | B(p_B) \rangle. \quad (6)$$

In the semi-leptonic case we can trivially factorize $G(M^2)$ and obtain

$$\begin{aligned} G^{LeP}(M^2) = & \frac{G_F^2}{2} |V_{cb}|^2 \sum_X (2\pi)^4 \delta^4(M - p_X) \langle 0 | (\bar{\ell}\gamma^\mu(1 - \gamma_5)\nu)(\bar{\nu}\gamma^\nu(1 - \gamma_5)\ell) | 0 \rangle \\ & \langle B(p_B) | (\bar{b}\gamma_\mu(1 - \gamma_5)c) | \bar{D}(p_{\bar{D}}) X \rangle \langle \bar{D}(p_{\bar{D}}) X | (\bar{c}\gamma_\nu(1 - \gamma_5)b) | B(p_B) \rangle. \end{aligned} \quad (7)$$

The next steps are to insert heavy quark fields in the effective Hamiltonian and considering m_b and m_c as large scales, to perform a SDE as it has been explained in [1]. In the leading order of the SDE, $G^{Lep}(M^2)$ reads

$$G^{Lep}(M^2) = \frac{G_F^2}{2} |V_{cb}|^2 P_{\mu\nu}^{Lep}(M) \quad (8)$$

$$\sum_X \langle B(v) | [\bar{b}_v \gamma^\mu (1 - \gamma_5) c_v] | \bar{D}(v') X \rangle \langle \bar{D}(v') X | [\bar{c}_{v'} \gamma^\nu (1 - \gamma_5) b_v] | B(v) \rangle,$$

where v is the velocity of the B meson, v' the one of the \bar{D} meson and $P_{\mu\nu}^{Lep}$ is a tensor originating from the contraction of the lepton fields in the effective Hamiltonian. This tensor is given by

$$P_{\mu\nu}^{Lep}(M) = A(M^2)(M^2 g_{\mu\nu} - M_\mu M_\nu) + B(M^2) M_\mu M_\nu. \quad (9)$$

Neglecting the lepton masses, we obtain at tree level

$$A(M^2) = -\frac{1}{3\pi} \Theta(M^2) \text{ and } B(M^2) = 0. \quad (10)$$

We shall now consider the non-leptonic case. The non-leptonic case is more complex because two transitions are possible: the right charm $\bar{b} \rightarrow \bar{c}$ transition and the wrong charm one $\bar{b} \rightarrow c$. The wrong charm transition was treated in [2] and we shall not come back to this issue there since this channel is extremely suppressed in the semi-leptonic case and was neglected in [1] and our aim in this section is strictly to establish the link between the right charm semi-leptonic and non-leptonic decays. Another difficulty is that factorization can only be performed in the $1/N_C$ limit. This concept is known to be valuable for non-leptonic exclusive B mesons decays [8]. In this limit the octet operators vanish. Thus we obtain

$$G^{NL}(M^2) = \frac{G_F^2}{2} |V_{cb} V_{q_1 q_2}^*|^2 |C_1|^2 \sum_X \sum_{X'} (2\pi)^4 \delta^4(M - p_X - p_{X'}) \quad (11)$$

$$\langle B(p_B) | (\bar{b} \gamma_\mu (1 - \gamma_5) c) | \bar{D}(p_{\bar{D}}) X \rangle \langle 0 | (\bar{q}_1 \gamma^\mu (1 - \gamma_5) q_2) | X' \rangle$$

$$\langle X' | (\bar{q}_2 \gamma^\nu (1 - \gamma_5) q_1) | 0 \rangle \langle \bar{D}(p_{\bar{D}}) X | (\bar{c} \gamma_\nu (1 - \gamma_5) b) | B(p_B) \rangle,$$

where the q_i 's stand for quarks. We see that assuming that X and X' are disjoint which is certainly the case in the leading order of the $1/N_C$ limit, we can at once apply the completeness relation for X' and we just find ourselves in the same situation as in the semi-leptonic case.

For the quark transition $b \rightarrow \bar{c} u d$ we have $q_1 = u$ and $q_2 = d$, i.e. we have two light quarks whose masses can be neglected just as the one of the lepton in the semi-leptonic case. We obtain

$$P_{\mu\nu}^{NL}(M) = N_C P_{\mu\nu}^{Lep}(M), \quad (12)$$

where N_C is the color number, and

$$G^{NL}(M^2) = \frac{G_F^2}{2} |V_{cb}V_{ud}|^2 P_{\mu\nu}^{NL}(M) \quad (13)$$

$$\sum_X \langle B(v) | [\bar{b}_v \gamma^\mu (1 - \gamma_5) c_{v'}] | \bar{D}(v') X \rangle \langle \bar{D}(v') X | [\bar{c}_{v'} \gamma^\nu (1 - \gamma_5) b_v] | B(v) \rangle.$$

The transition $b \rightarrow c\bar{c}s$ can be treated in the same fashion. In that case the mass of the c quark in the loop cannot be neglected. We obtain

$$P_{\mu\nu}^{NL}(M) = A(M^2)(M^2 g_{\mu\nu} - M_\mu M_\nu) + B(M^2) M_\mu M_\nu, \quad (14)$$

where $A(M^2)$ and $B(M^2)$ are given by

$$A(M^2) = -\frac{N_C}{3\pi} \left(1 + \frac{m_c^2}{2M^2}\right) \left(1 - \frac{m_c^2}{M^2}\right)^2 \Theta(M^2 - m_c^2), \quad (15)$$

$$B(M^2) = \frac{N_C}{2\pi} \frac{m_c^2}{M^2} \left(1 - \frac{m_c^2}{M^2}\right)^2 \Theta(M^2 - m_c^2),$$

at tree level. As explained in [2], we shall set $m_c = 1.0$ GeV to parameterize the higher order QCD corrections to the current $b \rightarrow c\bar{c}s$.

We can now establish the connection between the semi-leptonic and the non-leptonic form factors. The differential decay width for the semi-leptonic decays is given by

$$\frac{d\Gamma}{dy} = \frac{G_F^2}{12\pi^3} |V_{cb}|^2 m_D^3 \sqrt{y^2 - 1} \left[(m_B - m_D)^2 E_S(y) \right. \quad (16)$$

$$\left. + (m_B + m_D)^2 E_P(y) - M^2 (E_V(y) + E_A(y)) \right],$$

where $y = v \cdot v'$ and where the invariant mass M^2 is given by

$$M^2 = m_B^2 + m_D^2 - 2ym_B m_D. \quad (17)$$

The differential decay width for the right charm non-leptonic decays is then given by

$$\frac{d\Gamma}{dy} = C_1^2 N_C \frac{G_F^2}{12\pi^3} |V_{cb}V_{ud}^*|^2 m_D^3 \sqrt{y^2 - 1} \left[(m_B - m_D)^2 E_S(y) \right. \quad (18)$$

$$\left. + (m_B + m_D)^2 E_P(y) - M^2 (E_V(y) + E_A(y)) \right]$$

$$+ C_1^2 \frac{G_F^2}{4\pi^2} |V_{cb}V_{cs}^*|^2 m_D^3 \sqrt{y^2 - 1} \left[(B(M^2) - A(M^2)) ((m_B - m_D)^2 E_S(y) \right.$$

$$\left. + (m_B + m_D)^2 E_P(y)) + A(M^2) M^2 (E_V(y) + E_A(y)) \right],$$

where $A(M^2)$ and $B(M^2)$ are given in (15). We see that the right charm semi-leptonic and non-leptonic decay widths are given in terms of the same form factors

$$\begin{aligned}
4m_B m_D E_S(v \cdot v') &= \sum_X \langle B(v) | [\bar{b}_v c_{v'}] | \bar{D}(v') X \rangle \langle \bar{D}(v') X | [\bar{c}_{v'} b_v] | B(v) \rangle \\
-4m_B m_D E_P(v \cdot v') &= \sum_X \langle B(v) | [\bar{b}_v \gamma_5 c_{v'}] | \bar{D}(v') X \rangle \langle \bar{D}(v') X | [\bar{c}_{v'} \gamma_5 b_v] | B(v) \rangle \\
4m_B m_D E_V(v \cdot v') &= \sum_X \langle B(v) | [\bar{b}_v \gamma^\mu c_{v'}] | \bar{D}(v') X \rangle \langle \bar{D}(v') X | [\bar{c}_{v'} \gamma_\mu b_v] | B(v) \rangle \\
4m_B m_D E_A(v \cdot v') &= \sum_X \langle B(v) | [\bar{b}_v \gamma^\mu \gamma_5 c_{v'}] | \bar{D}(v') X \rangle \langle \bar{D}(v') X | [\bar{c}_{v'} \gamma_\mu \gamma_5 b_v] | B(v) \rangle.
\end{aligned} \tag{19}$$

One important point should be stressed. This set (19) of non-perturbative form factors describes a transition from a B meson into a state with a D meson whatever the intermediate state might be. It has been shown in [1] that we can determine these matrix elements in the semi-leptonic case using constraints from the heavy quark symmetry (HQS) and a saturation assumption. These non-perturbative form factors were given in [1] for each single decay channel. So the non-leptonic right charm $B \rightarrow \bar{D}X$ decays can be deduced from the semi-leptonic ones. Note that we have neglected the renormalization group improvement which had been considered in [1] since this effect is small. Therefore we set $C_{11} = C_3 = 1$ and $C_{18} = 0$ in the set of non-perturbative form factors given in [1].

After the connection between the non-leptonic and the semi-leptonic case has been established, we shall consider $B_s \rightarrow \bar{D}_s X$ and $B_s \rightarrow D_s X$ decays.

3 The decays $B_s \rightarrow \bar{D}_s X$ and $B_s \rightarrow D_s X$

As mentioned previously the effective weak Hamiltonian is identical to the one of the $B \rightarrow \bar{D}X$ case, therefore the equations (16) and (18) do also describe the right charm decay of a B_s meson into a \bar{D}_s meson if one replaces m_B by m_{B_s} and m_D by m_{D_s} . We have a new set a non-perturbative form factors

$$\begin{aligned}
4m_{B_s} m_{D_s} E_S(v \cdot v') &= \sum_X \langle B_s(v) | [\bar{b}_v c_{v'}] | \bar{D}_s(v') X \rangle \langle \bar{D}_s(v') X | [\bar{c}_{v'} b_v] | B_s(v) \rangle \\
-4m_{B_s} m_{D_s} E_P(v \cdot v') &= \sum_X \langle B_s(v) | [\bar{b}_v \gamma_5 c_{v'}] | \bar{D}_s(v') X \rangle \langle \bar{D}_s(v') X | [\bar{c}_{v'} \gamma_5 b_v] | B_s(v) \rangle \\
4m_{B_s} m_{D_s} E_V(v \cdot v') &= \sum_X \langle B_s(v) | [\bar{b}_v \gamma^\mu c_{v'}] | \bar{D}_s(v') X \rangle \langle \bar{D}_s(v') X | [\bar{c}_{v'} \gamma_\mu b_v] | B_s(v) \rangle \\
4m_{B_s} m_{D_s} E_A(v \cdot v') &= \sum_X \langle B_s(v) | [\bar{b}_v \gamma^\mu \gamma_5 c_{v'}] | \bar{D}_s(v') X \rangle \langle \bar{D}_s(v') X | [\bar{c}_{v'} \gamma_\mu \gamma_5 b_v] | B_s(v) \rangle.
\end{aligned} \tag{20}$$

Once again we can find a parameterization for these non-perturbative form factors using the semi-leptonic decays. We shall consider the s quark as being massless and we can therefore use the very same heavy quark symmetry relations as in the

case $B \rightarrow \bar{D}X$. As it has been argued in [1], the HQS implies that at $v \cdot v' = 1$ the inclusive rate is saturated by the exclusive decays into the lowest lying spin symmetry doublet \bar{D}_s and \bar{D}_s^* . The \bar{D}_s^* subsequently decays into \bar{D}_s mesons and thus at $v \cdot v' = 1$ the sum of the exclusive rates for $B_s \rightarrow \bar{D}_s \ell^+ \nu$ and $B_s \rightarrow \bar{D}_s^* \ell^+ \nu$ is equal to the one-particle inclusive semi-leptonic rate $B_s \rightarrow \bar{D}_s \ell^+ \nu X$. Making use of this assumption and of the spin projection matrices for the heavy B_s and $\bar{D}_s^{(*)}$ mesons, we obtain:

$$E_i(v \cdot v') = \frac{1}{16} |\text{Tr}\{\gamma_5(1 + \not{v})\Gamma_i(1 + \not{v}')\gamma_5\}|^2 |\xi(y)|^2 + \frac{1}{16} \sum_{Pol} |\text{Tr}\{\gamma_5(1 + \not{v})\Gamma_i(1 + \not{v}')\not{\epsilon}\}|^2 |\xi(y)|^2 \text{Br}(\bar{D}_s^* \rightarrow \bar{D}_s X), \quad (21)$$

where i stands for S, P, V or A , the sum is over the polarization of the D^* meson and $\xi(y) = 1 - 0.84(y - 1)$ is the Isgur-Wise function measured by CLEO [4]. The branching ratio $\text{Br}(\bar{D}_s^* \rightarrow \bar{D}_s X)$ is the new input and since a D_s^{*-} always decays into a D_s^- , we have $\text{Br}(\bar{D}_s^* \rightarrow \bar{D}_s X) = 100\%$. We then obtain

$$\begin{aligned} E_S^{B_s^0 D_s^-}(y) &= \frac{1}{4}(y + 1)^2 |\xi(y)|^2 \\ E_P^{B_s^0 D_s^-}(y) &= \frac{1}{4}(y^2 - 1) |\xi(y)|^2 \\ E_V^{B_s^0 D_s^-}(y) &= \frac{1}{2}(y + 1)(2 - y) |\xi(y)|^2 \\ E_A^{B_s^0 D_s^-}(y) &= -\frac{1}{2}(y + 2)(y + 1) |\xi(y)|^2. \end{aligned} \quad (22)$$

The non-leptonic decays $B_s \rightarrow \bar{D}_s X$ can be calculated using these non-perturbative form factors. It is clear that this saturation assumption is a crude approximation, but it is well motivated by the HQS at $y = 1$ and the available phase space is not very large, this has to be treated as a theoretical uncertainty due to non-perturbative physics. The results obtained for the semi-leptonic decays rates in $B \rightarrow \bar{D}X \ell \nu$ [1] give us some confidence in our method.

We shall now consider the wrong charm decays of a B_s meson. They are induced by the quark transition $\bar{b} \rightarrow c$. The wrong charm $B_s^0 \rightarrow D_s^{*+} X$ decay width can be estimated using the method described in [2], which corresponds to a rescaling of the parton calculation. In the leading order of the $1/N_C$ and of the $1/m_{B_s}$ expansions, the differential decay width reads

$$\frac{d\Gamma}{dy} = \frac{3G_F^2 C_1^2}{2\pi^3 M^2} \sqrt{y^2 - 1} m_{D_s}^3 |V_{cb} V_{cs}^*|^2 y (M^2 - m_{D_s}^2)^2 \Theta(M^2 - m_c^2) F, \quad (23)$$

where F is a channel dependent non-perturbative form factor. We have

$$F^{B_s^0 D_s^{*+}} = f(1 + 3\Gamma(D_s^* \rightarrow D_s X')) = 4f, \quad (24)$$

where X' is a pion or a photon and f is the constant defined in [2]; we had $f = 0.121$. Note that the wrong charm decay is being modeled and we have restricted our-selves to the so-called model 2 of [2] since this model seems to yield better results than model 1.

4 Discussion of the results

In table 1, we compare our predictions with the experimental data found in [3]. In the semi-leptonic case the method yields results which agree with the data. Note that we have considered the τ lepton as being massive. On the other hand, it is not clear if the non-leptonic decays are problematic, our results are in the experimental error range though at the inferior limit. One should keep in mind that we had estimated in [2] that corrections to our calculation could be fairly large and in the worst case up to 30%. It would be interesting to measure the rate $\Gamma(B_s \rightarrow \bar{D}_s^{*-} X)$ to test the agreement between theory and experiment in this channel. Remember that for the decays $B \rightarrow \bar{D}/DX$ described in [2], theory and experiment looked to be in agreement for the $B \rightarrow \bar{D}^*/D^*X$ decays and in disagreement for $B \rightarrow \bar{D}/DX$ decays although this could be accidental, for a discussion of this problem see [2].

Data is sparse on one-particle inclusive B_s decays, especially no spectra are available. It would be instructive to compare the spectra to check if the same discrepancy appears as in [2], where the spectra for the $B \rightarrow \bar{D}^*/D^*X$ meson decays seemed to be described correctly and on the other hand the spectra for the decays of a $B \rightarrow \bar{D}/DX$ were not compatible with the experimental data, especially at the non recoil point where the method should work at its best, this effect being therefore very difficult to understand. Although the extension of the method developed for one-particle inclusive B decays to B_s decays is trivial, the results we have obtained are interesting especially in the perspective of B factories. These results could also be used to study mixing induced one-particle inclusive CP asymmetries in the B_s system [6], this allows to determine the weak angle γ , which is known to be very difficult.

If the problems encountered in the one-particle inclusive B decays [2] were not present in B_s decays, one could constrain the kind of diagrammatic topologies contributing to the one-particle inclusive B decays. In B decays as well as in B_s decays we have assumed that the dominant diagrammatical topology contributing to the right charm decay rates is spectator like. This study of B_s decays once confronted to more precise experimental results could allow to test the influence of the light spectator quark.

Mode	Br (theory)	Br (data from [3])
$B_s^0 \rightarrow D_s^- X$	64.9%	$(92 \pm 33)\%$ $(8.1 \pm 2.5)\%$
$B_s^0 \rightarrow D_s^+ X$	3.3%	
$B_s^0 \rightarrow D_s^- \ell^+ \nu X$	9.1%	
$B_s^0 \rightarrow D_s^- \tau^+ \nu_\tau X$	2.7%	
$B_s^0 \rightarrow D_s^{*-} X$	49.6%	
$B_s^0 \rightarrow D_s^{*+} X$	2.5%	
$B_s^0 \rightarrow D_s^{*-} \ell^+ \nu X$	7%	
$B_s^0 \rightarrow D_s^{*-} \tau^+ \nu_\tau X$	2%	

Table 1: Comparison of our results with data. To get branching ratios, we used $\tau_{B_s^0} = 1.55$ ps.

5 Conclusions

We have clarified the link between the non-perturbative form factors of the semi-leptonic and non-leptonic $B \rightarrow \bar{D}X$. We have applied a method described in [1] and [2] to semi-leptonic and non-leptonic $B_s \rightarrow \bar{D}_s X$ and $B_s \rightarrow D_s X$ decays, this can be done easily by modifying the saturation assumption. It is too early to see if the same problems which were encountered in [2] do also appear in our case, the reason being the lack of experimental data. Our results are compatible with current experimental knowledge.

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